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National Renewable Energy Laboratory

**A SUMMARY OF LIFE CYCLE ASSESSMENT STUDIES CONDUCTED  
ON BIOMASS, COAL, AND NATURAL GAS SYSTEMS**

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## ABSTRACT

A series of life cycle assessments (LCA) have been conducted on biomass, coal, and natural gas systems in order to quantify the environmental benefits and drawbacks of each. The power generation options that were studied are: 1) a biomass-fired integrated gasification combined cycle (IGCC) system using a biomass energy crop, 2) a direct-fired biomass power plant using biomass residue, 3) a pulverized coal (PC) boiler representing an average U.S. coal-fired power plant, 4) a system cofiring biomass residue with coal, and 5) a natural gas combined cycle power plant. Each assessment was conducted in a cradle-to-grave manner to cover all processes necessary for the operation of the power plant, including raw material extraction, feed preparation, transportation, waste disposal, and recycling. A summary of the energy balance, global warming potential (GWP), air emissions, and resource consumption for each system is given.

## INTRODUCTION

The generation of electricity, and the consumption of energy in general, result in consequences to the environment. Using renewable resources and incorporating advanced technologies such as integrated gasification combined cycle (IGCC) may result in less environmental damage, but to what degree, and with what trade-offs? Life cycle assessment studies have been conducted on various power generating options in order to better understand the environmental benefits and drawbacks of each technology. Material and energy balances were used to quantify the emissions, energy use, and resource consumption of each process required for the power plant to operate. These include feedstock procurement (mining coal, extracting natural gas, growing dedicated biomass, collecting residue biomass), transportation, manufacture of equipment and intermediate materials (e.g., fertilizers, limestone), construction of the power plant, decommissioning, and any necessary waste disposal.

The systems chosen are:

- a biomass-fired integrated gasification combined cycle (IGCC) system using a biomass energy crop (hybrid poplar)
- a direct-fired biomass power plant using biomass residue (urban, primarily)
- a pulverized coal boiler with steam cycle, representing the average for coal-fired power plants in the U.S. today
- a system cofiring biomass residue with coal (15% by heat input will be presented here)
- a natural gas combined cycle power plant.

Each study was conducted independently and can therefore stand alone, giving a complete picture of each power generation technology. However, the resulting emissions, resource consumption, and energy requirements of each system can ultimately be compared, revealing the environmental benefits and drawbacks of the renewable and fossil based systems.



## RESULTS

### *System Energy Balance*

The total energy consumed by each system includes the fuel energy consumed plus the energy contained in raw and intermediate materials that are consumed by the systems. Examples of the first type of energy use are the fuel spent in transportation, and fossil fuels consumed by the fossil-based power plants. The second type of energy is the sum of the energy that would be released during combustion of the material (if it is a fuel) and the total energy that is consumed in delivering the material to its point of use. Examples of this type of energy consumption are the use of natural gas in the manufacture of fertilizers and the use of limestone in flue-gas desulfurization. The combustion energy calculation is applied where non-renewable fuels are used, reflecting the fact that the fuel has a potential energy that is being consumed by the system. The combustion energy of renewable resources, those replenished at a rate equal to or greater than the rate of consumption, is not subtracted from the net energy of the system. This is because, on a life cycle basis, the resource is not being consumed. To determine the net energy balance of each system, the energy used in each process block is subtracted from the energy produced by the power plant. The total system energy consumption by each system is shown in Table 1.

Table 1: Total System Energy consumption

System	Total energy consumed (kJ/kWh)
Biomass-fired IGCC using hybrid poplar	231
Direct-fired biomass power plant using biomass residue	125
Average coal	12,575
Biomass / coal cofiring (15% by heat input)	10,118
Natural gas IGCC	8,377

In order to examine the process operations that consume the largest quantities of energy within each system, two energy measurement parameters were defined. First, the energy delivered to the grid divided by the total fossil-derived energy consumed by each system was calculated. This measure, known as the net energy ratio, is useful for assessing how much energy is generated for each unit of fossil fuel consumed. The other measure, the external energy ratio, is defined to be the energy delivered to the grid divided by the total non-feedstock energy to the power plant. That is, the energy contained in the coal and natural gas used at the fossil-based power plants is excluded. The external energy ratio assesses how much energy is generated for each unit of upstream energy consumed. Because the energy in the biomass is considered to be both generated and consumed within the boundaries of the system, the net energy ratio and external energy ratio will be the same for the biomass-only cases (biomass-fired IGCC and direct-fired biomass). In calculating the external energy ratio, we are essentially treating the coal and natural gas fed to the fossil power plants as renewable fuels, so that upstream energy consumption can be compared. Figure 1 shows the energy results for each case studied.

As expected, the biomass-only plants consume less energy overall, since the consumption of non-renewable coal and natural gas at the fossil plants results in net energy balances of less than one. The direct-fired biomass residue case delivers the most amount of electricity per unit of energy consumed. This is because the energy used to provide a usable residue biomass to the plant is fairly low. Despite its higher plant efficiency, the biomass IGCC plant has a lower net energy balance than the direct-fired plant because a significant amount of energy was required to grow the biomass as a dedicated crop. Resource limitations, however, may necessitate the use of energy crops in the future. Cofiring biomass with coal slightly increases the energy ratios over those for the coal-only case, even though the plant efficiency was derated by 0.9 percentage points.

In calculating the external energy ratios, the feedstocks to the power plants were excluded, essentially treating all feedstocks as renewable. Because of the perception that biomass fuels are of lower quality than fossil fuels, it was expected that the external energy ratios for the fossil-based systems would be substantially higher than those of the biomass-based systems. The opposite is true, however, due to the large amount of energy that is consumed in upstream operations in the fossil-based systems. The total non-feedstock energy consumed by the systems is shown in Table 2. In the coal case, 35% of this energy is consumed in operations relating to flue-gas cleanup, including limestone procurement. Mining the coal consumes 25% of this energy, while transporting the coal is responsible for 32%. Greater than 97% of the upstream energy consumption related to the natural gas IGCC system is due to natural gas extraction and pipeline transport steps, including fugitive losses. Although upstream processes in the biomass systems also consume energy, shorter transportation distances and the fact that flue-gas desulfurization is not required, reduce the total energy burden.

Table 2: Non-feedstock Energy Consumption

System	Non-feedstock energy consumed (kJ/kWh)
Biomass-fired IGCC using hybrid poplar	231
Direct-fired biomass power plant using biomass residue	125
Average coal	702
Biomass / coal cofiring (15% by heat input)	614
Natural gas IGCC	1,718

### ***Global Warming Potential***

Figure 2 shows the net emissions of greenhouse gases, using the 100-year values from the Intergovernmental Panel on Climate Change. CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O were quantified for these studies. The biomass IGCC system has a much lower GWP than the fossil systems because of the absorption of CO<sub>2</sub> during the biomass growth cycle. The direct-fired biomass system has a highly negative rate of greenhouse gas emissions because of the avoided methane generation associated with biomass decomposition that would have occurred had the residue not been used at the power plant.



Based on current disposal practices, it was assumed that 46% of the residue biomass used in the direct-fired and cofiring cases would have been sent to a landfill and that the remainder would end up as mulch and other low-value products. Decomposition studies reported in the literature were used to determine that approximately 9% of the carbon in the biomass residue would end up as  $\text{CH}_4$  were it not used at the power plant, while 61% would end up as  $\text{CO}_2$ . The remaining carbon is resistant to decomposition in the landfill, either due to inadequate growth conditions for the microbes or because of the protective nature of the lignin compounds.

Sensitivity analyses demonstrated that even moderate amounts of soil carbon sequestration (1,900 kg/ha/seven-year rotation) would result in the biomass IGCC system having a zero-net greenhouse gas balance. Sequestration amounts greater than this would result in a negative release of greenhouse gases, and a system that removes carbon from the atmosphere overall. The base case presented here assumes that there will be no net change in soil carbon, as actual gains and losses will be very site specific.

The natural gas combined cycle has the lowest GWP of all fossil systems because of its higher efficiency, despite natural gas losses that increase net  $\text{CH}_4$  emissions. Cofiring biomass with coal at 15% by heat input reduces the GWP of the average coal-fired power plant by 18%.

#### ***Air Emissions***

Emissions of particulates,  $\text{SO}_x$ ,  $\text{NO}_x$ ,  $\text{CH}_4$ ,  $\text{CO}$ , and NMHCs are shown in Figure 3. Methane emissions are high for the natural gas case due to natural gas losses during extraction and delivery. The direct-fired biomass and coal/biomass cofiring cases have negative methane emissions, due to avoided decomposition processes (landfilling and mulching).  $\text{CO}$  and NMHCs are higher for the biomass case because of upstream diesel combustion during biomass growth and preparation. Cofiring reduces the coal system air emissions by approximately the rate of cofiring, with the exception of particulates, which are generated during biomass chipping.

#### ***Resource Consumption***

Figure 4 shows the total amount of non-renewable resources consumed by the systems. Limestone is used in significant quantities by the coal-fired power plants for flue-gas desulfurization. The natural gas IGCC plant consumes almost negligible quantities of resources, with the exception of the feedstock itself. The natural gas consumed in this case includes a 1.4% loss to the atmosphere during extraction and delivery.

### **SUMMARY**

Completing several life cycle assessment studies has allowed us to determine where biomass power systems reduce the environmental burden associated with power generation. The key comparative results can be summarized as follows:

- The GWP of generating electricity using a dedicated energy crop in an IGCC system is 4.7% of that of an average U.S. coal power system.
- Cofiring residue biomass at 15% by heat input reduces the greenhouse gas emissions and net energy consumption of the average coal system by 18% and 12%, respectively.

- The life cycle energy balances of the coal and natural gas systems are significantly lower than those of the biomass systems because of the consumption of non-renewable resources.
- Not counting the coal and natural gas consumed at the power plants in these systems, the net energy balance is still lower than that of the biomass systems because of energy used in processes related to flue gas clean-up, transportation, and natural gas extraction and coal mining.
- The biomass systems produce very low levels of particulates, NO<sub>x</sub>, and SO<sub>x</sub> compared to the fossil systems.
- System methane emissions are negative when residue biomass is used because of avoided decomposition emissions.
- The biomass systems consume very small quantities of natural resources compared to the fossil systems.
- Other than natural gas, the natural gas IGCC consumes almost no resources.

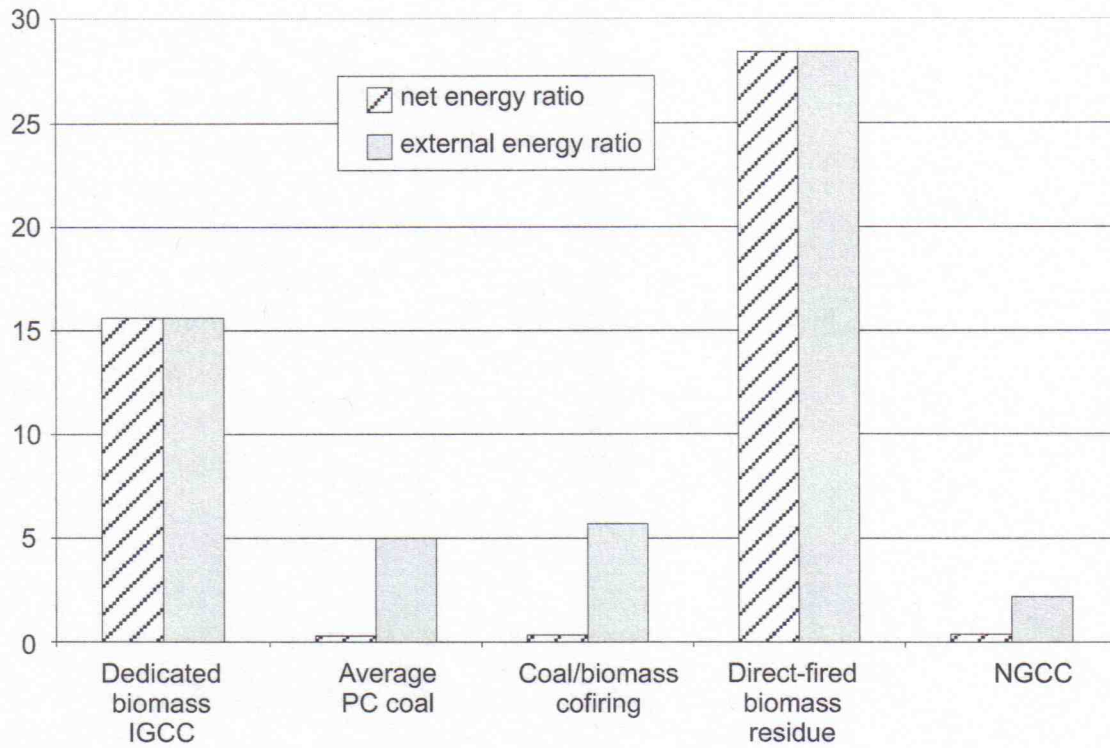
These results demonstrate quite clearly that, overall, biomass power provides significant environmental benefits over conventional fossil-based power systems. In particular, biomass systems can significantly reduce the amount of greenhouse gases that are produced, per kWh of electricity generated. Additionally, because the biomass systems use renewable energy instead of non-renewable fossil fuels, they consume very small quantities of natural resources and have a positive net energy balance. Cofiring biomass with coal offers us an opportunity to reduce the environmental burdens associated with the coal-fired power systems that currently generate over half of the electricity in the United States. Finally, by reducing NO<sub>x</sub>, SO<sub>x</sub>, and particulates, biomass power can improve local air quality.

## **FUTURE WORK**

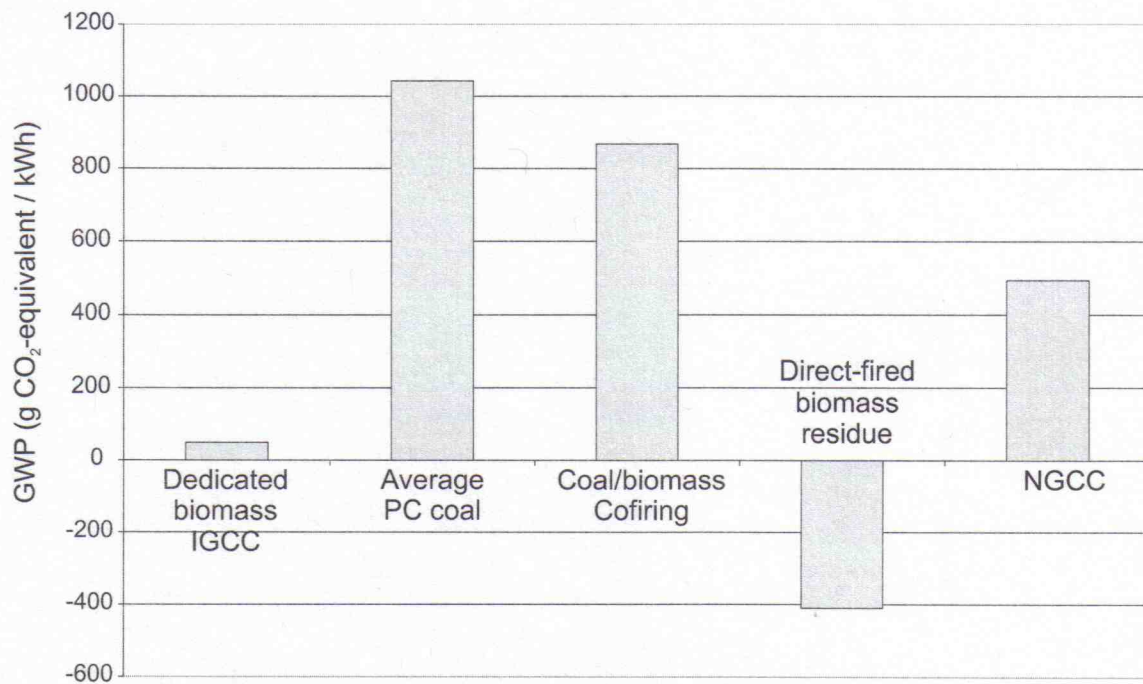
While these LCA studies have provided us with a quantitative assessment of the benefits and drawbacks of each of these power generation options, work still remains to be done. The studies should be updated periodically to incorporate new technological advances and relevant data. This is particularly true with the biomass IGCC study, where research work is being conducted on both feedstock development and power plant operation. Similarly, a coal IGCC system should be studied and included in this suite of analyses. Additionally, impact assessment methodologies used at NREL should be applied to the inventory results of these studies to provide better opportunities for data interpretation. There are also other biomass power systems that should be analyzed, in order to identify those technologies that have the potential to expand the benefits of clean biomass power. Finally, integration of economic cash flow models and these LCA models can quantify the cost of reducing the environmental burden of power generation.



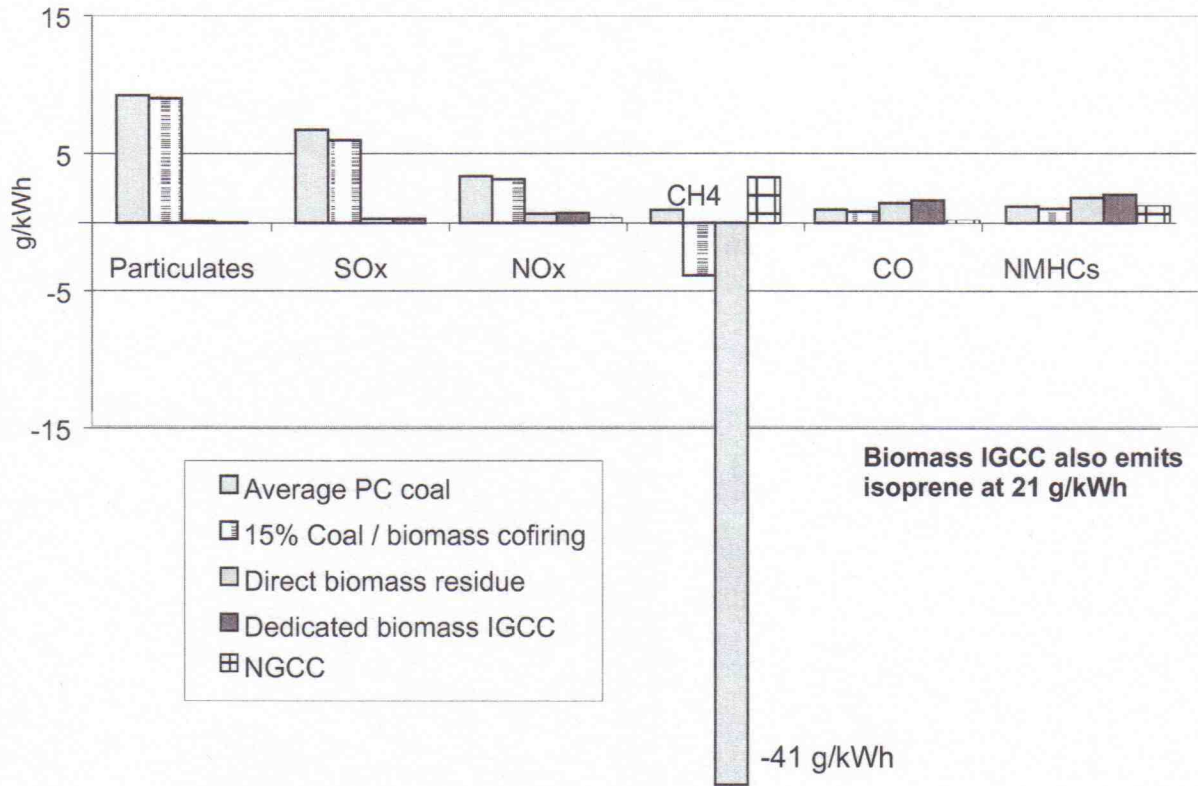
**Figure 1: Life Cycle Energy Balance**



**Figure 2: Net Life Cycle Greenhouse Gas Emissions**



### Figure 3: Other Air Emissions



### Figure 4: Resource Consumption

